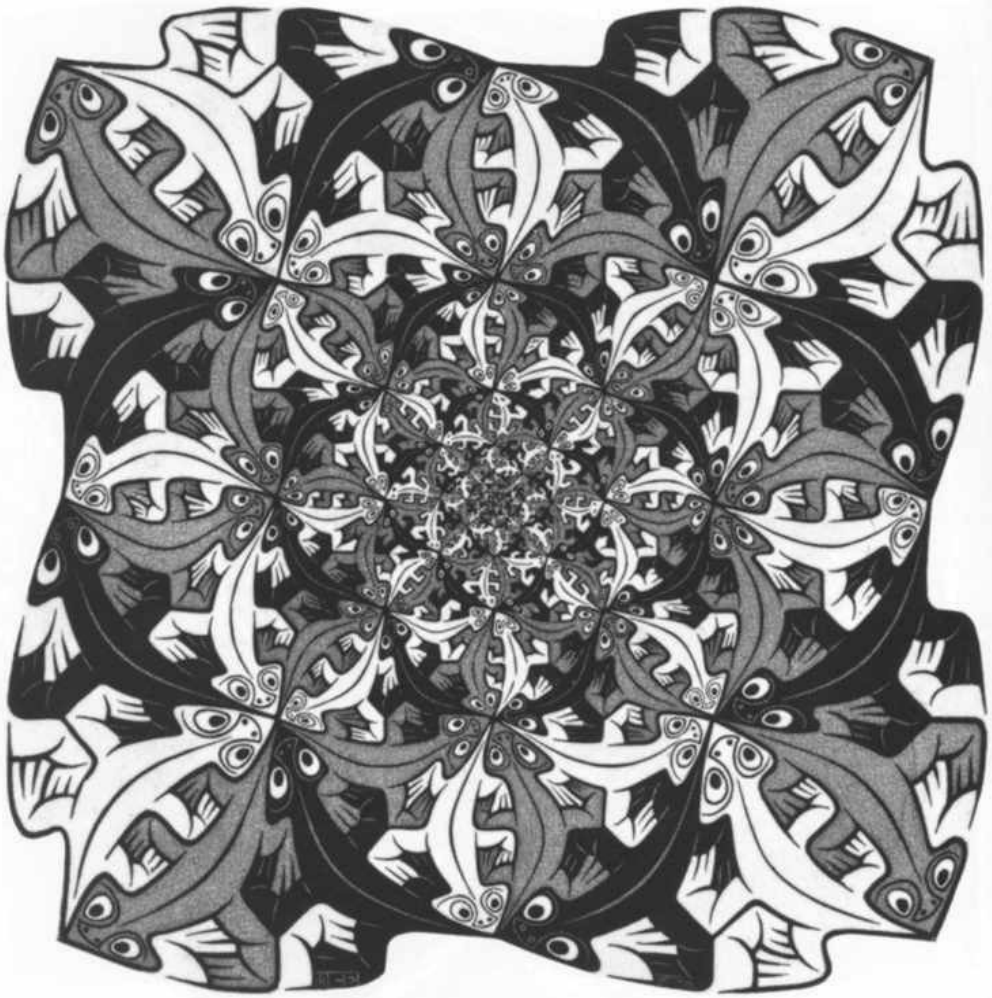

Evidence for an anomalous like-sign dimuon charge asymmetry

Research Progress Meeting at LBNL

9 September 2010

Marco Verzocchi
Fermilab, PPD

Outline

What DØ really measures: matter-antimatter asymmetry

Relation with CP violation in neutral B mesons

The experimental technique, determination of background fractions and asymmetries

Extraction of the b-physics asymmetry from two samples

Combination of the results, cross-checks, uncertainties

Comparisons and combinations with other measurements

Conclusions

The DØ Measurement

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Evidence for an Anomalous Like-Sign Dimuon Charge Asymmetry

Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW D **82,** 032001 (2010)

Evidence for an anomalous like-sign dimuon charge asymmetry

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Starting from a CP invariant initial state ($p\bar{p}$ collisions) the DØ Collaboration measures the raw asymmetry

$$A = \frac{N(\mu^+\mu^+) - N(\mu^-\mu^-)}{N(\mu^+\mu^+) + N(\mu^-\mu^-)}$$

Is the final state symmetric ?
Contributions from backgrounds ?
What are the sources of asymmetry ?

Matter-Antimatter Asymmetry

All astrophysical / cosmological observations consistent with matter-antimatter asymmetry at 10^{-10} level after the Big Bang

Models for generation of this asymmetry (Sakharov) require source of CP violation

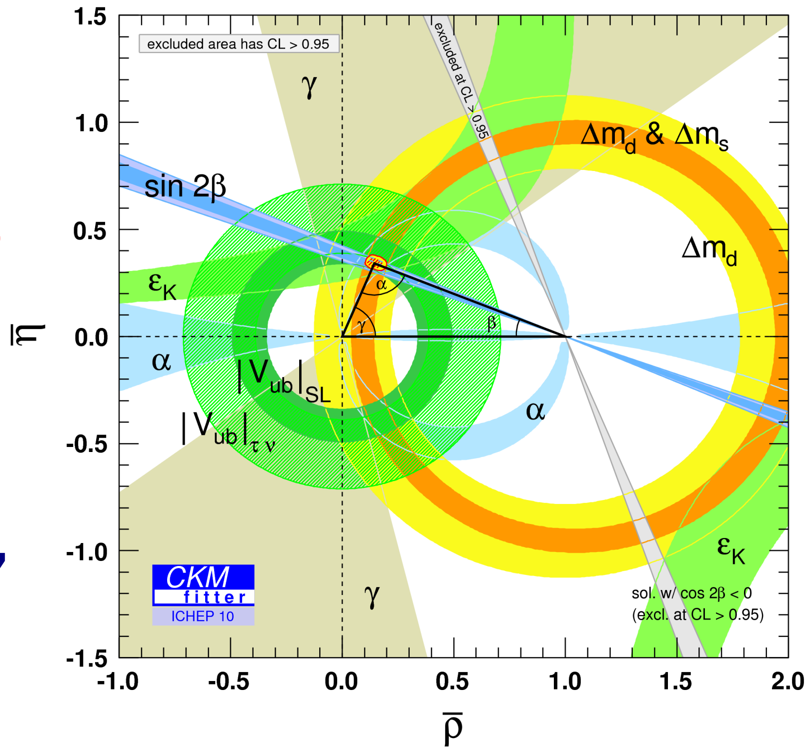
CP Violation in / beyond the SM

CP violation in the Standard Model arises from single phase in CKM matrix, experimental tests at b-factories and Tevatron

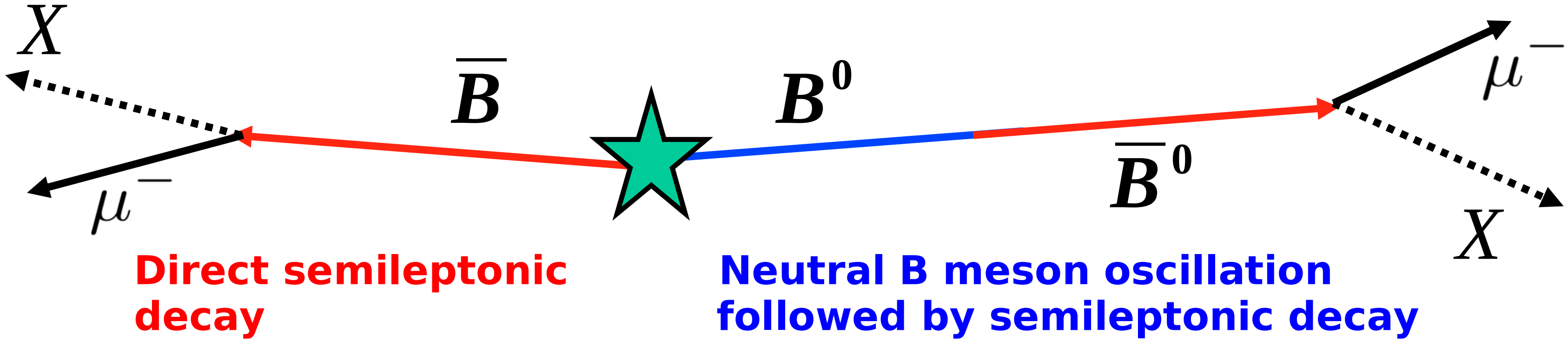
CP violation in the SM too small to generate observed matter-antimatter asymmetry

Motivate searches for additional sources of CP violation (B_s system, neutrinos)

One of few sources of same-sign dileptons is B physics (mixing of neutral B mesons)



Dimuon Charge Asymmetry



Measure CP violation *in mixing* via

$$\boxed{A^b_{\mathrm{sl}} = \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}}$$

Dimuon charge asymmetry of semileptonic B decays

Semileptonic Charge Asymmetry

Right sign decay: $B \rightarrow \mu^+ X$

Wrong sign decay: $\overline{B} \rightarrow \mu^+ X$ **(after oscillation $B \rightarrow \overline{B}$)**

$$\boxed{a_{\rm sl}^{b} = \frac{\Gamma(\overline{B} \rightarrow \mu^+ X) - \Gamma(B \rightarrow \mu^- X)}{\Gamma(\overline{B} \rightarrow \mu^+ X) + \Gamma(B \rightarrow \mu^- X)} = A_{\rm sl}^{b}}$$

Semileptonic charge asymmetry

Dimuon charge asymmetry

Define semileptonic charge asymmetries for B^0_d and B^0_s

$$\boxed{a_{\rm sl}^{q} = \frac{\Gamma(\overline{B}_q^0 \rightarrow \mu^+ X) - \Gamma(B_q^0 \rightarrow \mu^- X)}{\Gamma(\overline{B}_q^0 \rightarrow \mu^+ X) + \Gamma(B_q^0 \rightarrow \mu^- X)}} \quad q = d, s$$

A^b_{sl} at the Tevatron and CP Violation

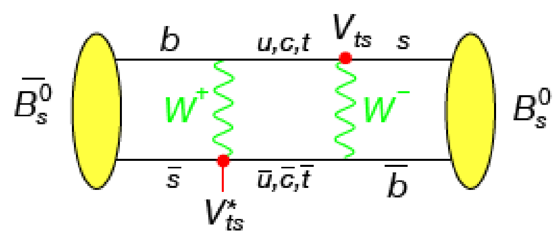
The quantity measured at the Tevatron is a linear combination of a^d_{sl} and a^s_{sl}

$$\boxed{A^b_{\rm sl} = (0.506 \pm 0.043)a^d_{\rm sl} + (0.494 \pm 0.043)a^s_{\rm sl}}$$

Large contribution from B^0_s at the Tevatron

Assuming CPT, mixing of neutral B mesons is described by:

$$i\frac{d}{dt}\begin{pmatrix} B_s^0 \\ \bar{B}_s^0\end{pmatrix} = \begin{pmatrix} M - \frac{i\Gamma}{2} & M_{12} - \frac{i\Gamma_{12}}{2} \\ M_{12}^* - \frac{i\Gamma_{12}^*}{2} & M - \frac{i\Gamma}{2}\end{pmatrix}\begin{pmatrix} B_s^0 \\ \bar{B}_s^0\end{pmatrix}$$



And $a^q_{\rm sl} = \frac{|\Gamma^{12}_q|}{|M^{12}_q|}\sin\phi_q = \frac{\Delta\Gamma_q}{\Delta M_q}\tan\phi_q.$ **with** $\phi_q \equiv \arg\left(-\frac{M^{12}_q}{\Gamma^{12}_q}\right).$

A^b_{sl} in the Standard Model

The SM predicts very small values of the asymmetries:

$$a^d_{\rm sl}({\rm SM}) = (-4.8^{+1.0}_{-1.2}) \times 10^{-4}$$

$$a^s_{\rm sl}({\rm SM}) = (2.1 \pm 0.6) \times 10^{-5},$$

$$A^b_{\rm sl}({\rm SM}) = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}.$$

Significant deviations from the SM values (zero for all practical purposes) would signal presence of new physics contributions to CP violation in mixing

Current experimental values:

$$a^d_{\rm sl} = -0.0047 \pm 0.0046$$ **(B-factories)**

$$a^s_{\rm sl} = -0.0017 \pm 0.0091$$ **(DØ: $B_s \rightarrow D_s \mu X$)**

Experimental Strategy (I)

Measure the raw asymmetries (regardless of muon source):

$$A = \frac{N(\mu^+\mu^+) - N(\mu^-\mu^-)}{N(\mu^+\mu^+) + N(\mu^-\mu^-)} \qquad a = \frac{n(\mu^+) - n(\mu^-)}{n(\mu^+) + n(\mu^-)}$$

Both contain contributions from A^b_{sl}, other processes with prompt muons, detector and reconstruction related backgrounds / asymmetries

Use data to determine the detector/reconstruction related effects with minimal input from simulation

Use known b/c hadrons branching fractions

Obtain two determinations of A^b_{sl} which are then combined to exploit correlations of signal and background contributions to minimize uncerntainty on A^b_{sl}

Experimental Strategy (II)

Measure the raw asymmetries (regardless of muon source):

$$A = \frac{N(\mu^+\mu^+) - N(\mu^-\mu^-)}{N(\mu^+\mu^+) + N(\mu^-\mu^-)} \qquad a = \frac{n(\mu^+) - n(\mu^-)}{n(\mu^+) + n(\mu^-)}$$

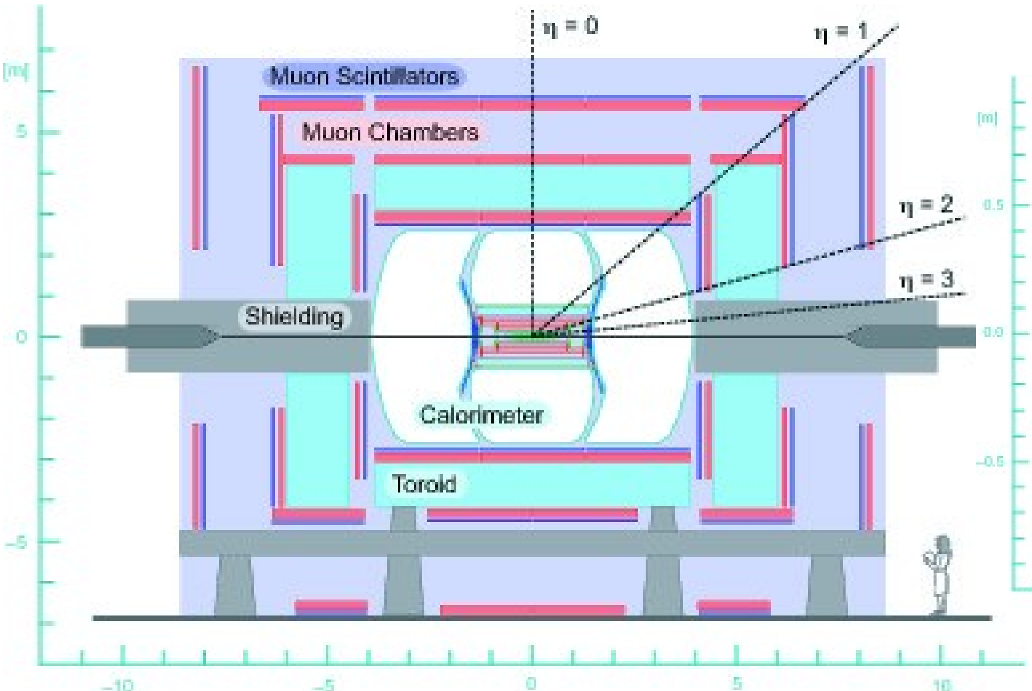
$A = K * A^{b}_{sl} + A_{bkg}$ $\qquad$ $a = k * A^{b}_{sl} + a_{bkg}$

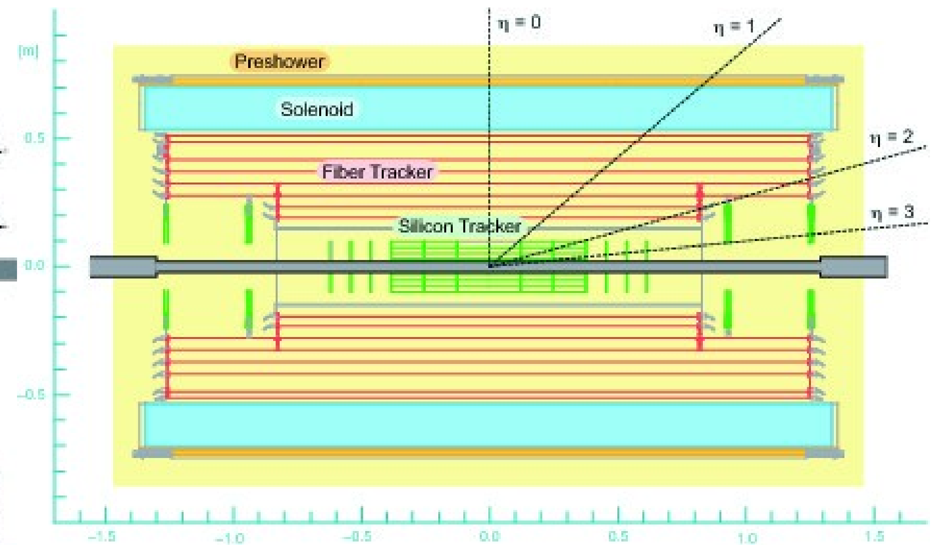
Expect K>*k* (2nd muon provides tagging of b production)

Determine A_{bkg} and a_{bkg}
Find the coefficients K and *k*
Extract the asymmetry A^{b}_{sl}

Central value of extracted from full data set only after the analysis method and all statistical and systematic uncertainties finalized

The DØ Experiment





Data collected between April 2002 and June 2009, 6.1 fb^{-1}

Use mixture of single/dimuon triggers, resulting in different spectra and angular distributions of single/dimuon events

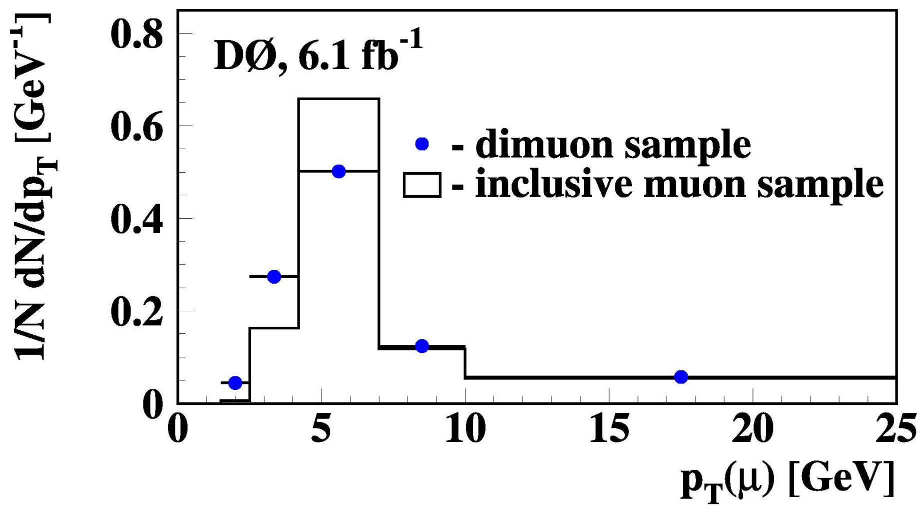
Two-magnets system, regular polarity changes, equalize datasets in 4 configurations (cancel most detector related asymmetries)

Event Selection

Good muons: reconstructed track matched to segment in inner/outer muon detectors ($|\eta|<2.2$)

Single muons: $1.5 < p_T < 25$ GeV,
$|p_z|>6.4$ GeV if $p_T<4.2$ GeV
good match to primary vertex (< 3 mm axial plane, <5 mm along beam)

Like-sign dimuons:
Two highest p_T like-sign 2μ
Matched to same vertex
Invariant mass > 2.8 GeV



Raw Asymmetries

From the inclusive muon sample (1.5G muons):

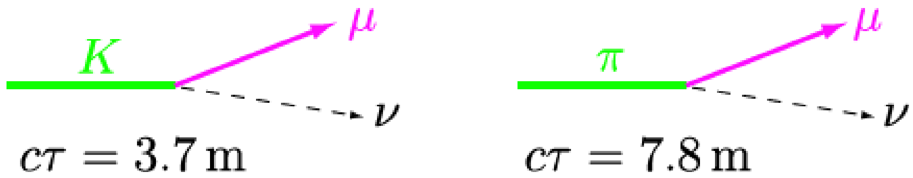
$$\boxed{a = \frac{n(\mu^+) - n(\mu^-)}{n(\mu^+) + n(\mu^-)} = (0.955 \pm 0.003)\%}$$

From 3.7M like-sign dimuon events:

$$\boxed{A = \frac{N(\mu^+\mu^+) - N(\mu^-\mu^-)}{N(\mu^+\mu^+) + N(\mu^-\mu^-)} = (0.564 \pm 0.053)\%}$$

Detector-Related Backgrounds

Decays in flight: $K \rightarrow \mu\nu$ and $\pi \rightarrow \mu\nu$



Punch-through of π,K,p

Muon mis-identification (wrong match between muon track segment and central track)

Other prompt muon sources (heavy flavor decays, EM decays of Resonances) accounted for via dilution factors

Detector-Related Backgrounds

Contributions to the single/like-sign dimuon asymmetries from backgrounds (keep only linear terms):

$$a_{\rm bkg} = f_K a_K + f_\pi a_\pi + f_p a_p + (1 - f_{\rm bkg})\delta$$
$$A_{\rm bkg} = F_K A_K + F_\pi A_\pi + F_p A_p + (2 - F_{\rm bkg})\Delta$$

Here: f_i,F_i – fraction of each particle (i=π,K,p) identified as muons
a_i,A_i – charge asymmetry of each track identified as a muon
δ,Δ - charge asymmetry of the muon reconstruction

$F_{bkg} = f_K+f_\pi+f_P$; $F_{bkg}=F_K+F_\pi+F_p$

Notation:lowercase letter for inclusive muon sample,
uppercase for like-sign dimuon sample

The Importance of Kaons

$$a_{\mathrm{bkg}} = f_K a_K + f_\pi a_\pi + f_p a_p + (1 - f_{\mathrm{bkg}})\delta$$
$$A_{\mathrm{bkg}} = F_K A_K + F_\pi A_\pi + F_p A_p + (2 - F_{\mathrm{bkg}})\Delta$$

Dominant contribution to asymmetries from K (others factor 10 smaller)

Caused by difference in interaction length between K^+/K^-

$\sigma(K^- d)$ = 80 mb, $\sigma(K^+ d)$= 33 mb @ 1 GeV

K^+ travel further than K^- , larger punch-through/decay probability

Cause positive asymmetry observed in data
(more antimatter than matter, not what you really want...)

Kaon Asymmetries (I)

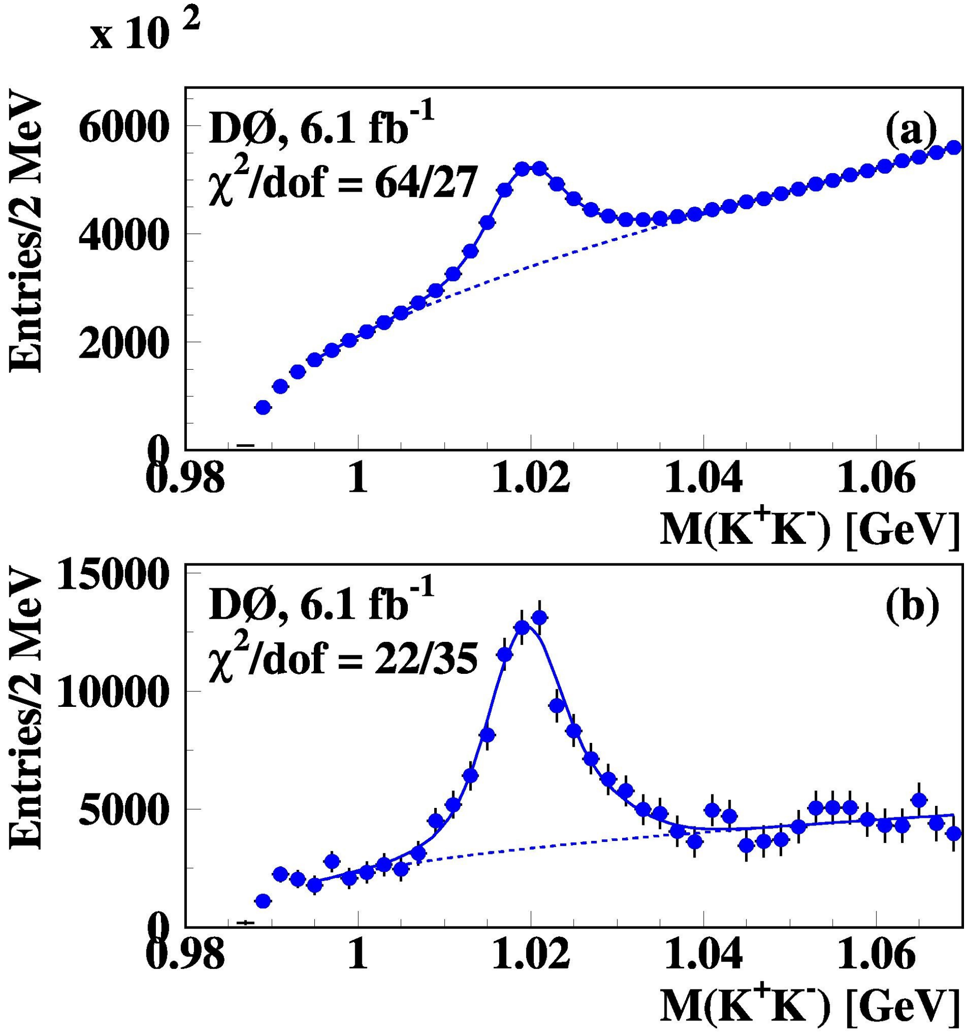
Reconstruct Φ and K^* decays in which one K is idenfied as μ

Build sum/difference of distributions for K^-/K^+

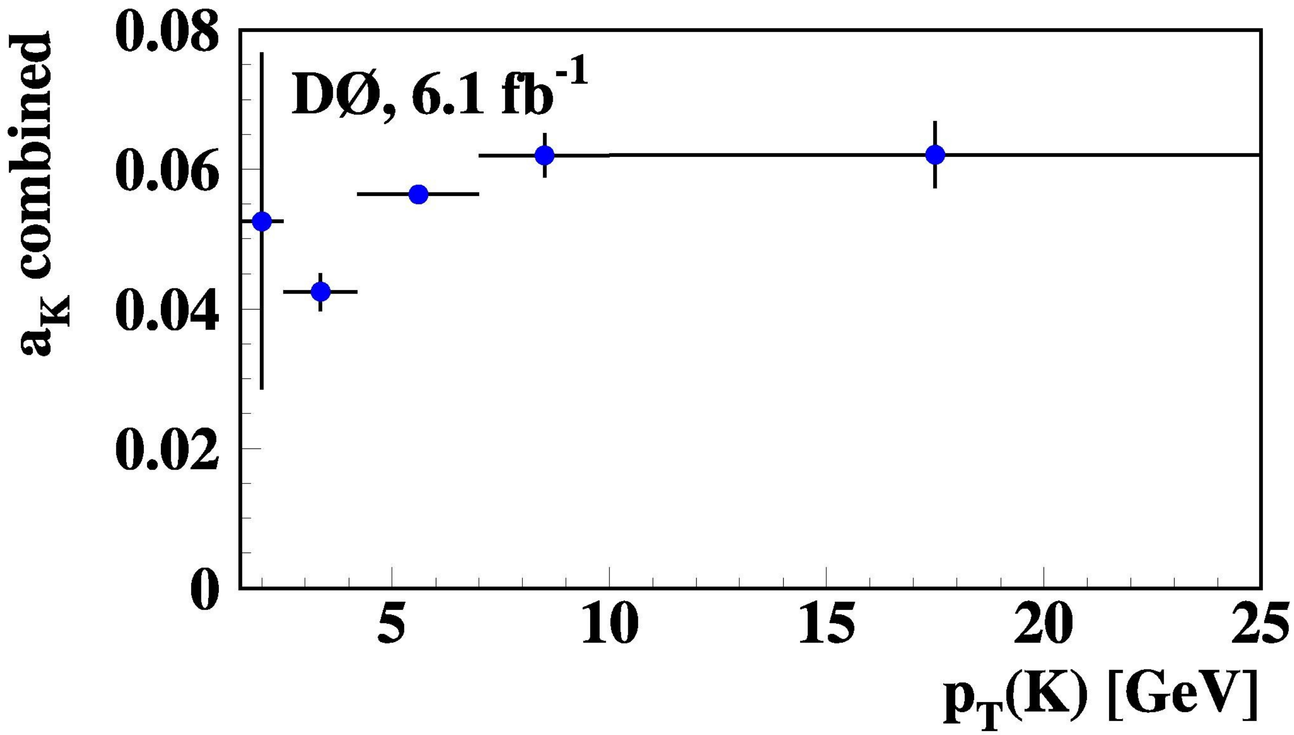
Ratio of histograms provides asymmetry

Correct for decay in flight (MC) (due to kink, not reconstructed in resonance)

Results from Φ and K^* consistent, combine



Kaon Asymmetries (II)



All asymmetries and contributions of different backgrounds determined in 5 bins of μ transverse momentum

Kaon Fractions

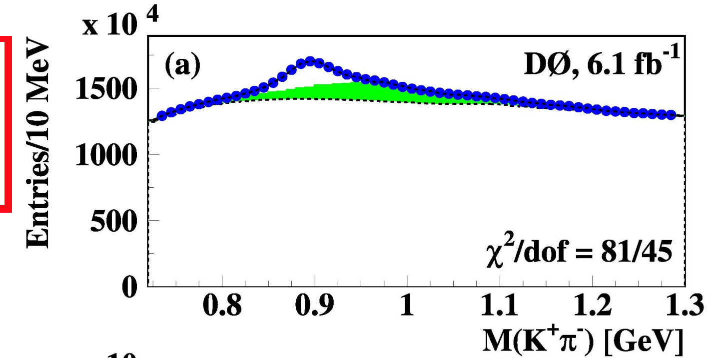
$$a_{\mathrm{bkg}} = f_K a_K + f_\pi a_\pi + f_p a_p + (1 - f_{\mathrm{bkg}})\delta$$
$$A_{\mathrm{bkg}} = F_K A_K + F_\pi A_\pi + F_p A_p + (2 - F_{\mathrm{bkg}})\Delta$$

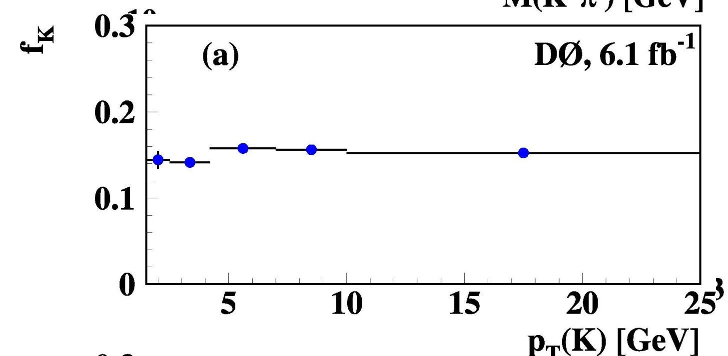
Reconstruct $K^{*0} \to K^+\pi^-$ and $K^{*+} \to K_s\pi^-$

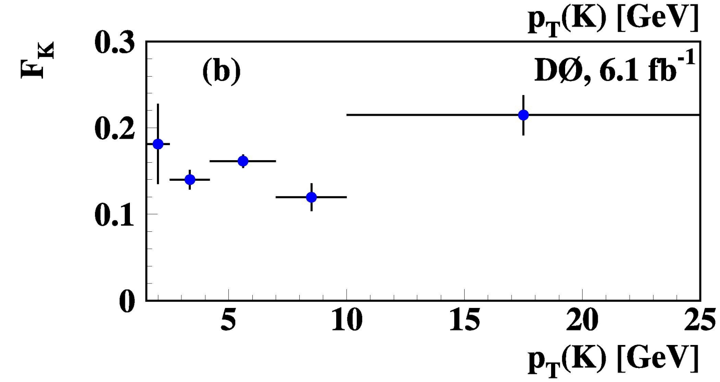
From the first derive f_{K^*0} and F_{K^*0}

Use isospin symmetry to obtain

$$F_K, f_K = \frac{N(K_S)}{N(K^{*+} \to K_S\pi^+)} f_{K^{*0}}, F_{K^{*0}}$$







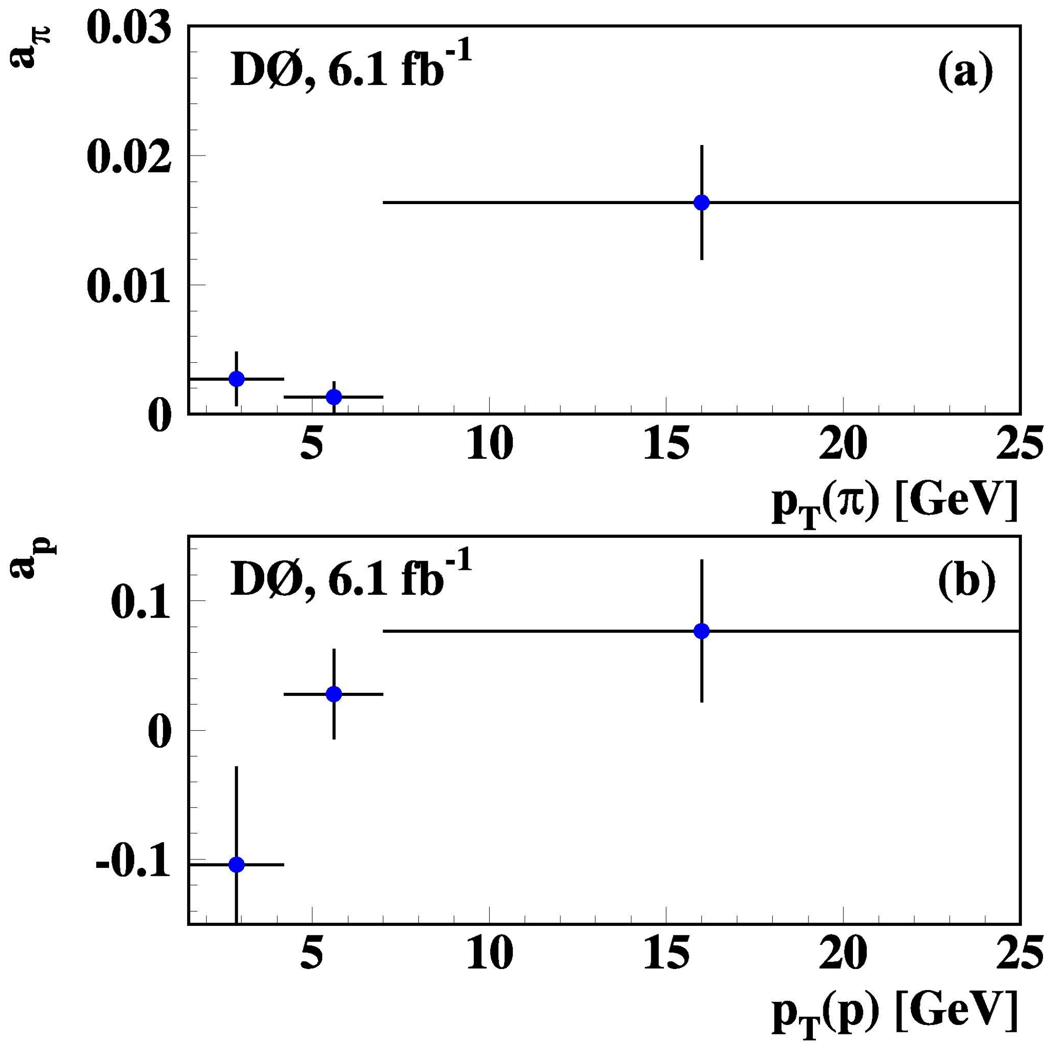
Pion and Proton Asymmetries

Pion/proton asymmetries obtained with similar technique using K_s and Λ decays

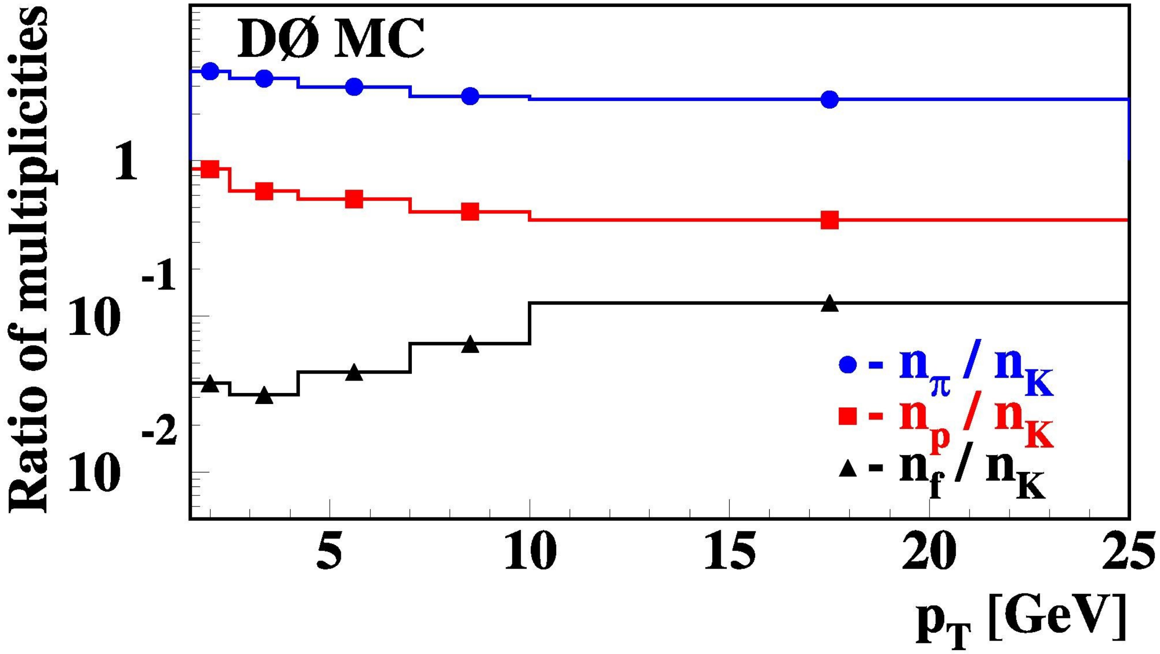
Factor 10 smaller (consistent with zero for protons)

Averaged over pT:

- $a_K = (+5.51 \pm 0.11)\%$
- $a_\pi = (+0.25 \pm 0.10)\%$
- $a_p = (+2.3 \pm 2.8)\%$



Other Background Fractions



Fractions of pions/protons obtained from fraction of kaons using ratio of particle multiplicities from event generator

Background Summary

$(1-f_{\rm bkg})$	f_K	f_π	f_p
$(58.1 \pm 1.4)\%$	$(15.5 \pm 0.2)\%$	$(25.9 \pm 1.4)\%$	$(0.7 \pm 0.2)\%$
	$a_K f_K$	$a_\pi f_\pi$	$a_p f_p$
	$(+0.854 \pm 0.018)\%$	$(+0.095 \pm 0.027)\%$	$(+0.012 \pm 0.022)\%$
	$A_K F_K$	$A_\pi F_\pi$	$A_p F_p$
	$(+0.828 \pm 0.035)\%$	$(+0.095 \pm 0.025)\%$	$(+0.000 \pm 0.021)\%$

Simulation (not used) gives very similar results

Similar background compositions for inclusive muon and like-sign dimuon samples

Reconstruction Asymmetry

$$a_{\text{bkg}} = f_K a_K + f_\pi a_\pi + f_p a_p + (1 - f_{\text{bkg}})\delta$$
$$A_{\text{bkg}} = F_K A_K + F_\pi A_\pi + F_p A_p + (2 - F_{\text{bkg}})\Delta$$

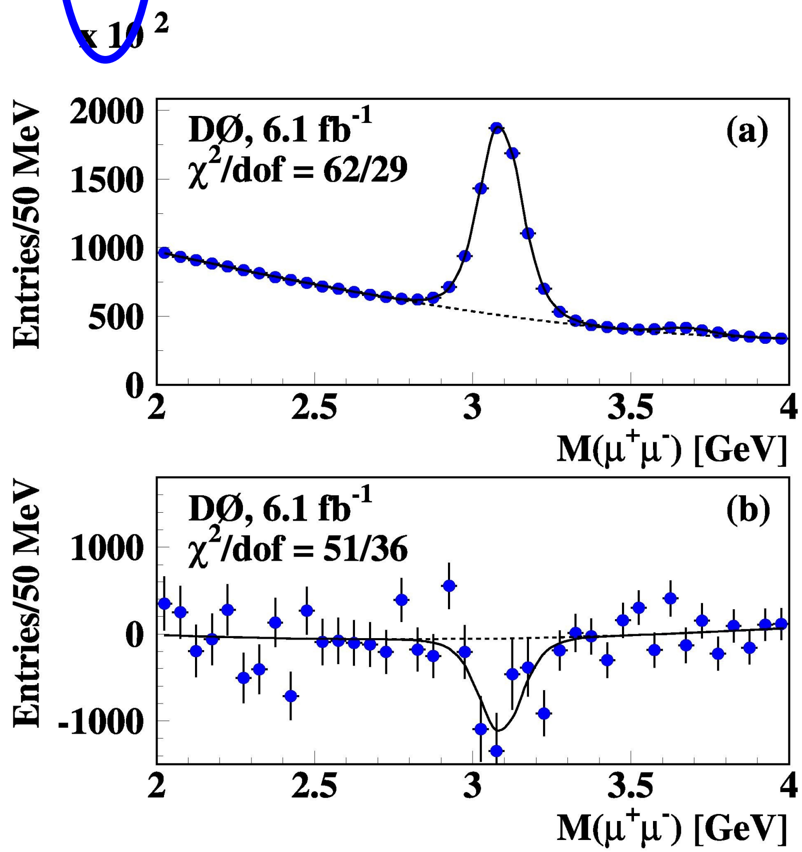
Reconstruct J/ψ using μ+track events

Repeat separately for different μ/track sign combinations

Derive asymmetry:

δ = (-0.076 ±0.028)%
Δ = (-0.068 ±0.023)%

Small residual asymmetries thanks to regular reversal of magnet polarities (otherwise 3% effect)



Dilution Factors

$$a - a_{\text{bkg}} = k A_{\text{sl}}^b$$
$$A - A_{\text{bkg}} = K A_{\text{sl}}^b$$

	Process		
T_1	$b \to \mu^- X$		
T_{1a}	$b \to \mu^- X$ (non-oscillating)		
T_{1b}	$\bar{b} \to b \to \mu^- X$ (oscillating)	$\longrightarrow A$	A_{sl}^b
T_2	$b \to c \to \mu^+ X$	$\longrightarrow A$	
T_{2a}	$b \to c \to \mu^+ X$ (non-oscillating)		
T_{2b}	$\bar{b} \to b \to c \to \mu^+ X$ (oscillating)		A_{sl}^b
T_3	$b \to c\bar{c}q$ with $c \to \mu^+ X$ or $\bar{c} \to \mu^- X$		
T_4	$\eta, \omega, \rho^0, \phi(1020), J/\psi, \psi' \to \mu^+\mu^-$		
T_5	$b\bar{b}c\bar{c}$ with $c \to \mu^+ X$ or $\bar{c} \to \mu^- X$	$\longrightarrow A$	
T_6	$c\bar{c}$ with $c \to \mu^+ X$ or $\bar{c} \to \mu^- X$		

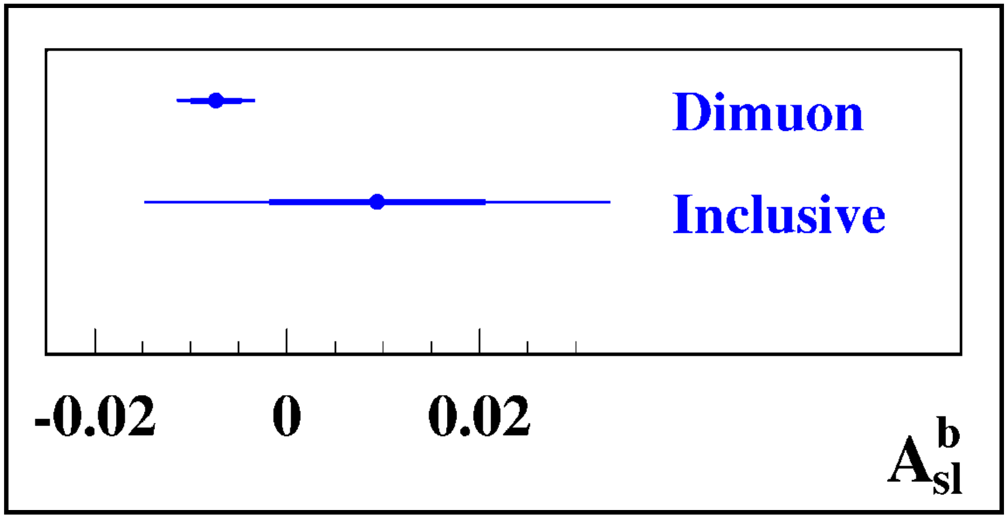
Use knowledge of hadrons with b/c quarks branching ratios / decay spectra to derive dilution factors

Take into account contributions from different decay chains

$$k = 0.041 \pm 0.003$$
$$K = 0.342 \pm 0.023$$

Note factor 10 difference !

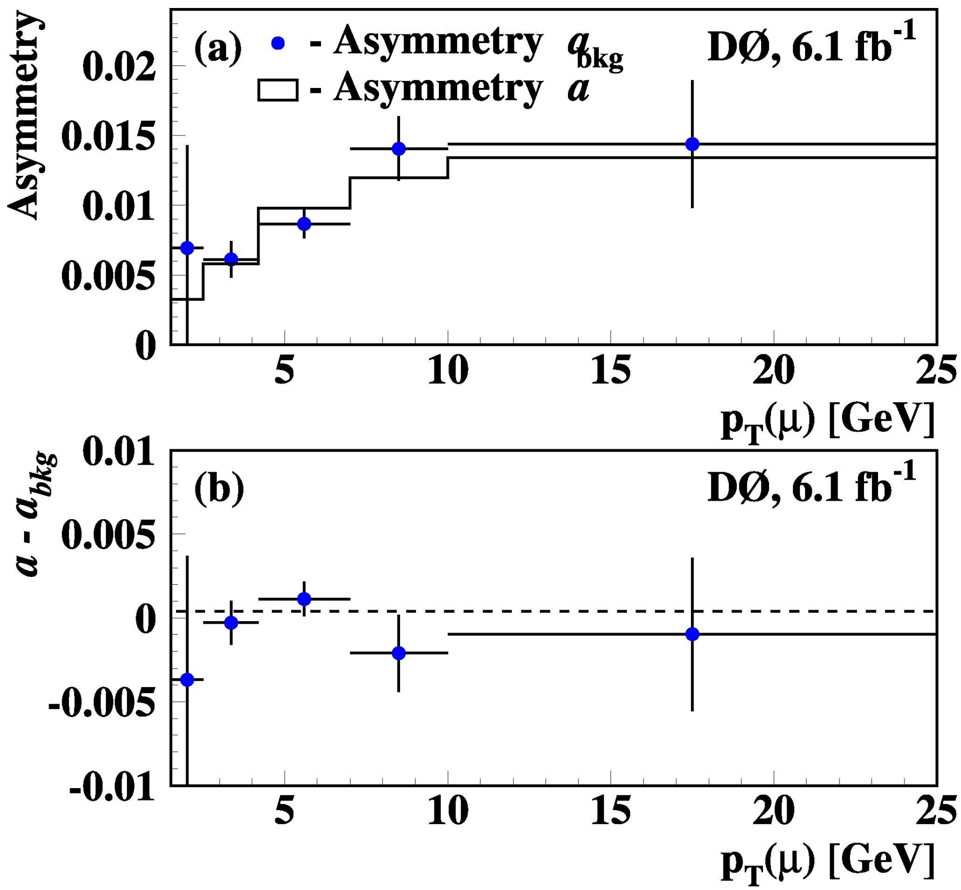
Individual Results



A^{b}_{sl} = (+0.94 ±1.12 (stat)±2.14 (syst))% (inclusive muons)

A^{b}_{sl} = (-0.736±0.266(stat)±0.305 (syst)) % (like-sign dimuons)

Consistency Checks (I)



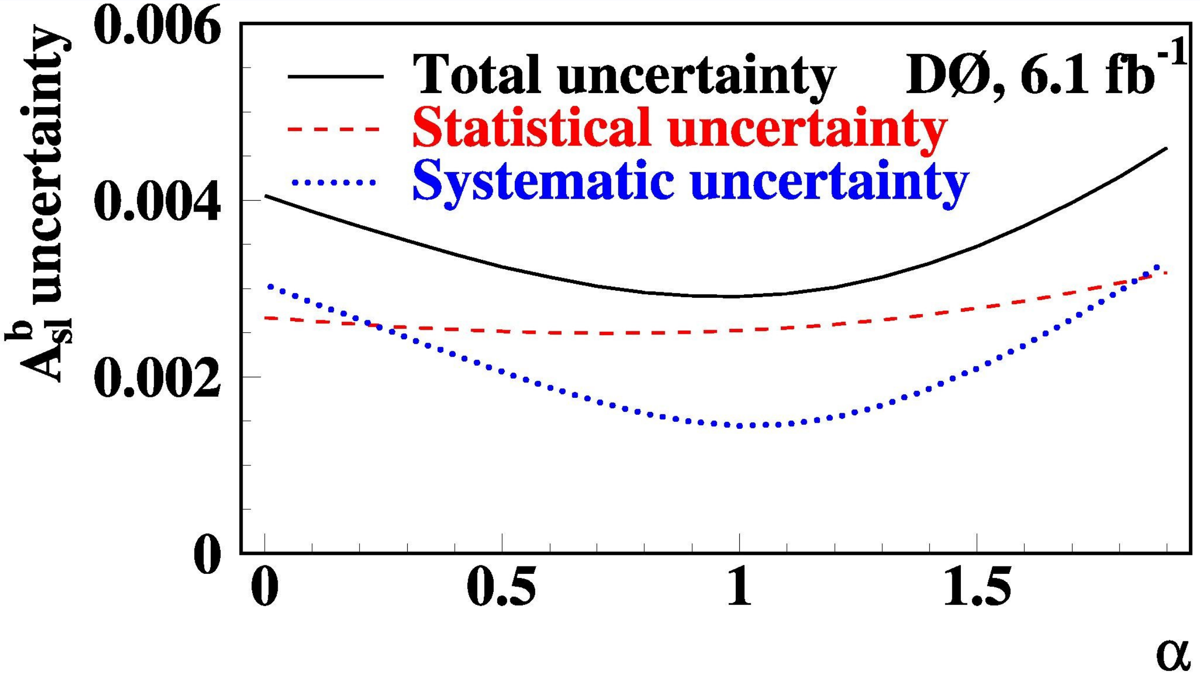
Dilution factor in inclusive muon case close to zero,asymmetry entirely due to background

Compare measured raw asymmetry with background asymmetry

Reproduce in magnitude and p_T dependence

a_{raw} = (0.955± 0.003)%
a_{bkg} = (0.917± 0.045)%

Combined Result



Minimum for α=0.959

Like-sign dimuons and inclusive muons have common source of backgrounds

Choose linear combination of asymmetries A' = (A-aa) which minimizes final uncertainty on A^b_{sl}

Combined Result

$$\boxed{A^b_{\rm sl} = (-0.957 \pm 0.251\,({\rm stat}) \pm 0.146\,({\rm syst}))\%}$$

3.2 standard deviations away from Standard Model prediction

$$\boxed{A^b_{\rm sl}(SM) = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}}$$

First evidence for anomalous source of CP violation in mixing of neutral B mesons

Result consistent with previous D0 measurement based on analysis of $1fb^{-1}$ of data (much larger MC dependence)

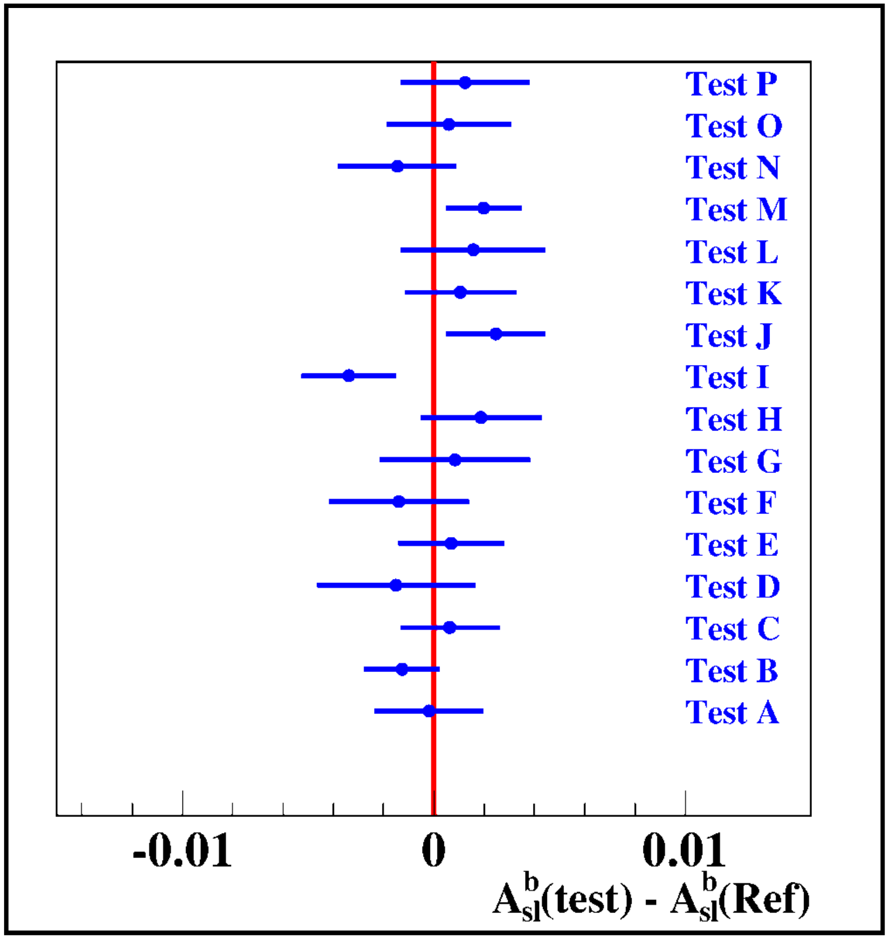
Systematics

Source	Inclusive muons $\delta\sigma(A^b_{\rm sl})$(62)	Like-sign dimuons $\delta\sigma(A^b_{\rm sl})$(63)	Combination $\delta\sigma(A^b_{\rm sl})$(65)
A or a (stat)	0.00066	0.00159	0.00179
f_K or F_K (stat)	0.00222	0.00123	0.00140
$P(\pi \to \mu)/P(K \to \mu)$	0.00234	0.00038	0.00010
$P(p \to \mu)/P(K \to \mu)$	0.00301	0.00044	0.00011
A_K	0.00410	0.00076	0.00061
A_π	0.00699	0.00086	0.00035
A_p	0.00478	0.00054	0.00001
δ or Δ	0.00405	0.00105	0.00077
f_K or F_K (syst)	0.02137	0.00300	0.00128
π, K, p multiplicity	0.00098	0.00025	0.00018
c_b or C_b	0.00080	0.00046	0.00068
Total statistical	0.01118	0.00266	0.00251
Total systematic	0.02140	0.00305	0.00146
Total	0.02415	0.00405	0.00290

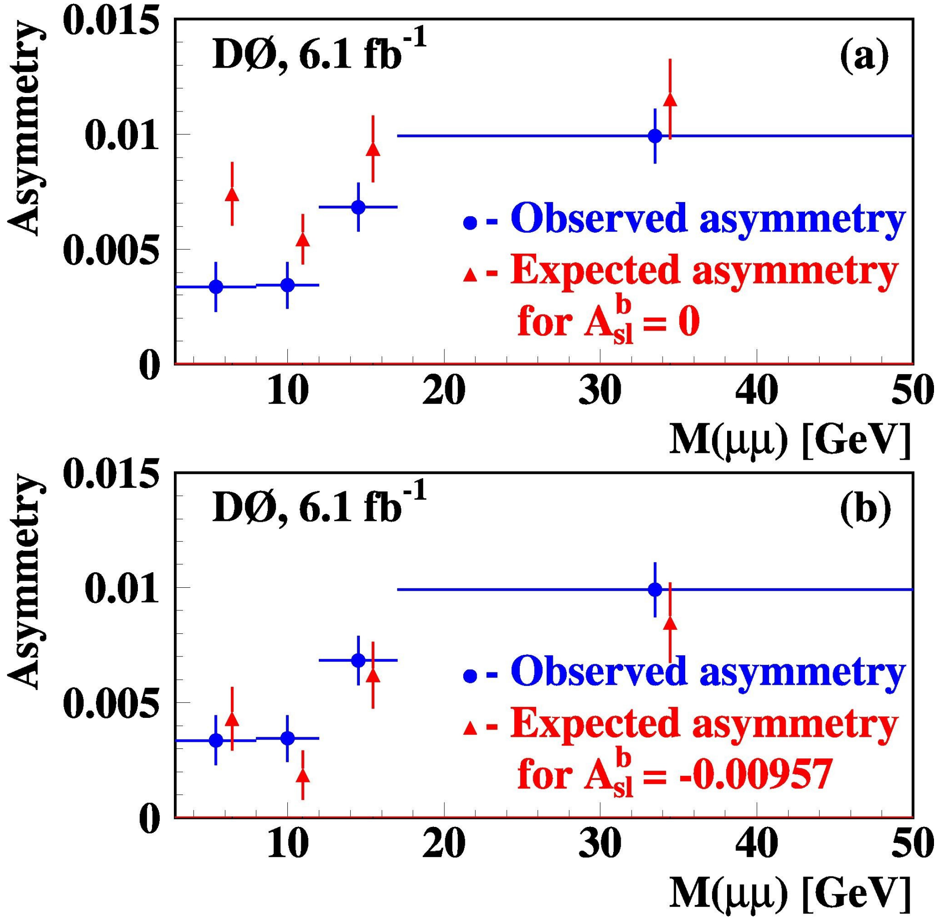
Consistency Checks (II)

Split dataset according to muon kinematic quantities, quality, data taking period, reduce possibility of background contaminations, enhance heavy quark contributions

Raw asymmetries may change up to 150%, however final result for A^b_{sl} is stable within 1 standard deviation in most cases



2b or not 2b ?



Do not have lifetime/flavor tagging to guarantee that asymmetry is from B hadrons

However expected asymmetry for A^b_{sl}=0 does not reproduce dependence from 2μ invariant mass

For measured value of A^b_s reproduce complicated kinematic dependence

Consistency with Other Results (I)

$$A^b_{\rm sl} = (0.506 \pm 0.043)a^d_{\rm sl} + (0.494 \pm 0.043)a^s_{\rm sl}$$

Here compare with measurements of a^d_{sl} and a^s_{sl} (B-factories and DØ in $B_s \to D_s\, \mu\, X$)

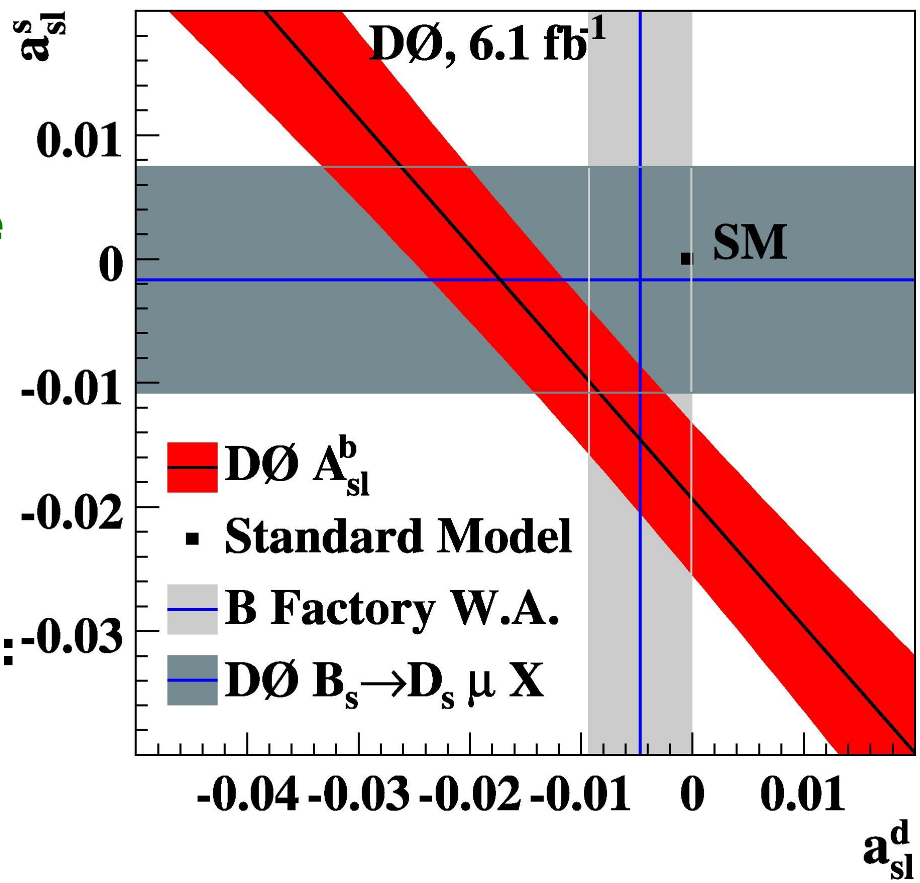
Consistent with world average (HFAG): a^d_{sl}=(-0.47± 0.46)%

Consistent with DØ measurement: a^s_{sl}=(-0.17± 0.91)%

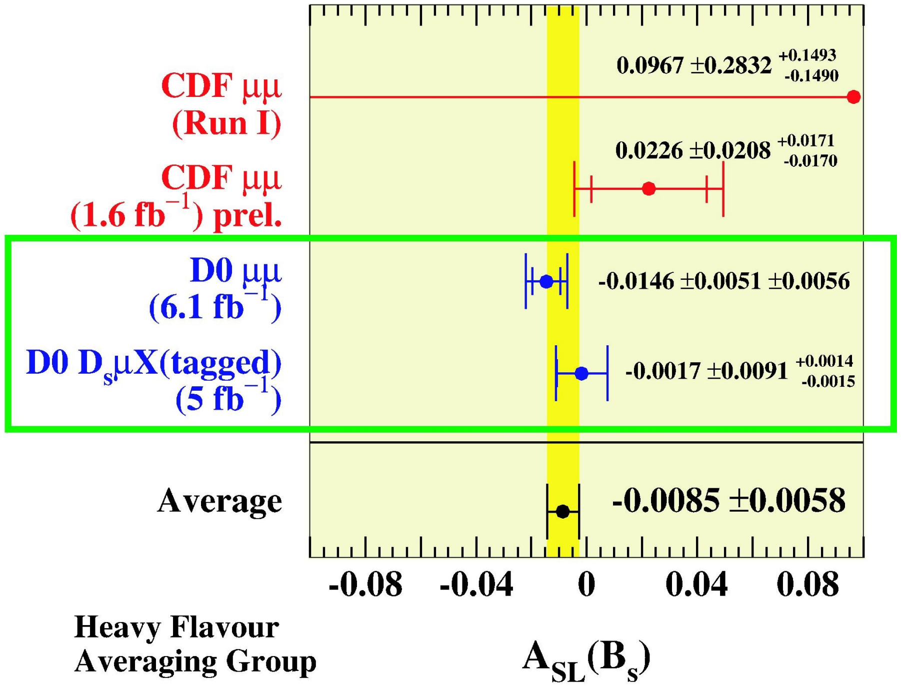
Use a^d_{sl} to obtain value for a^s_{sl} :

$$a^s_{\rm sl} = (-1.46 \pm 0.75)\%$$

$$a^s_{\rm sl}(SM) = (-0.0021 \pm 0.0006)\%$$

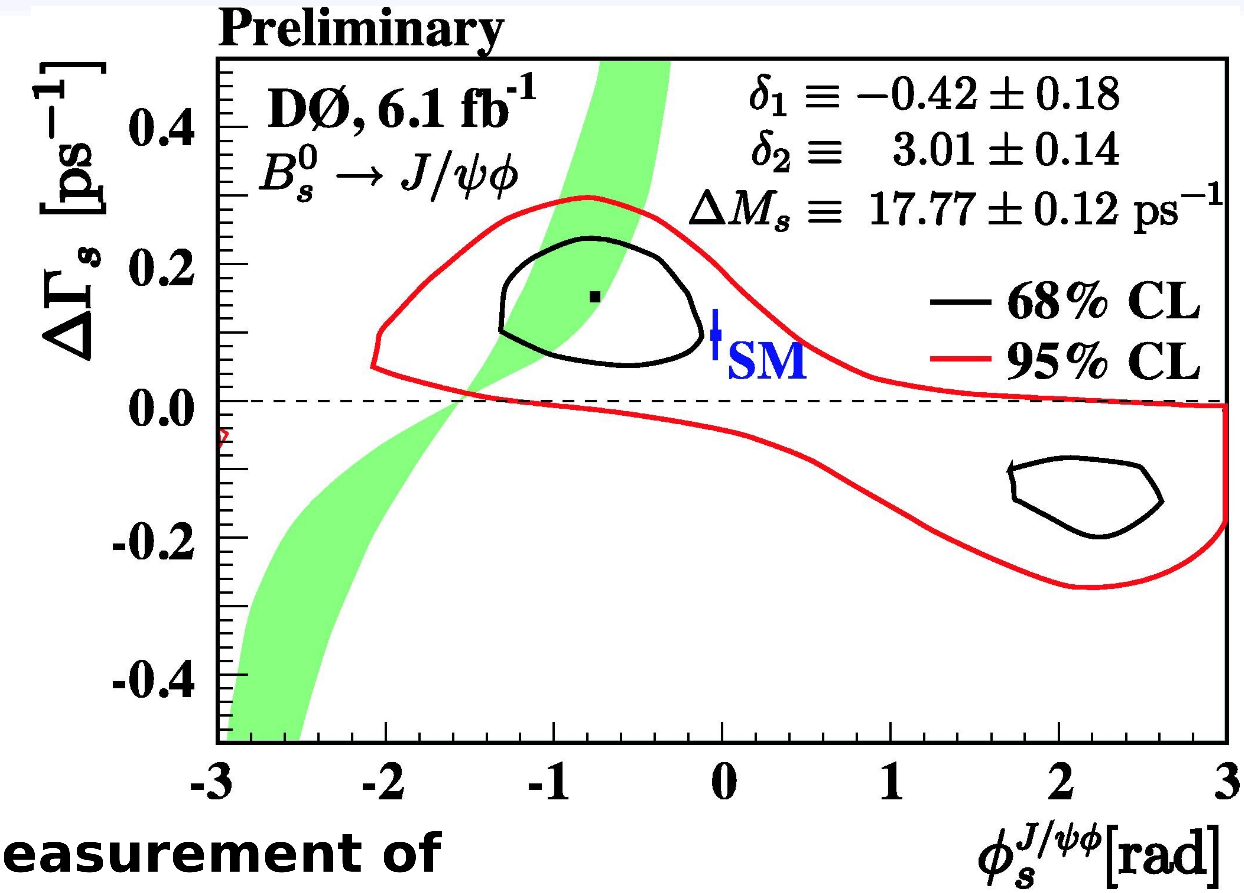


Consistency with other Results (II)



Other measurements of a^s_{sl}

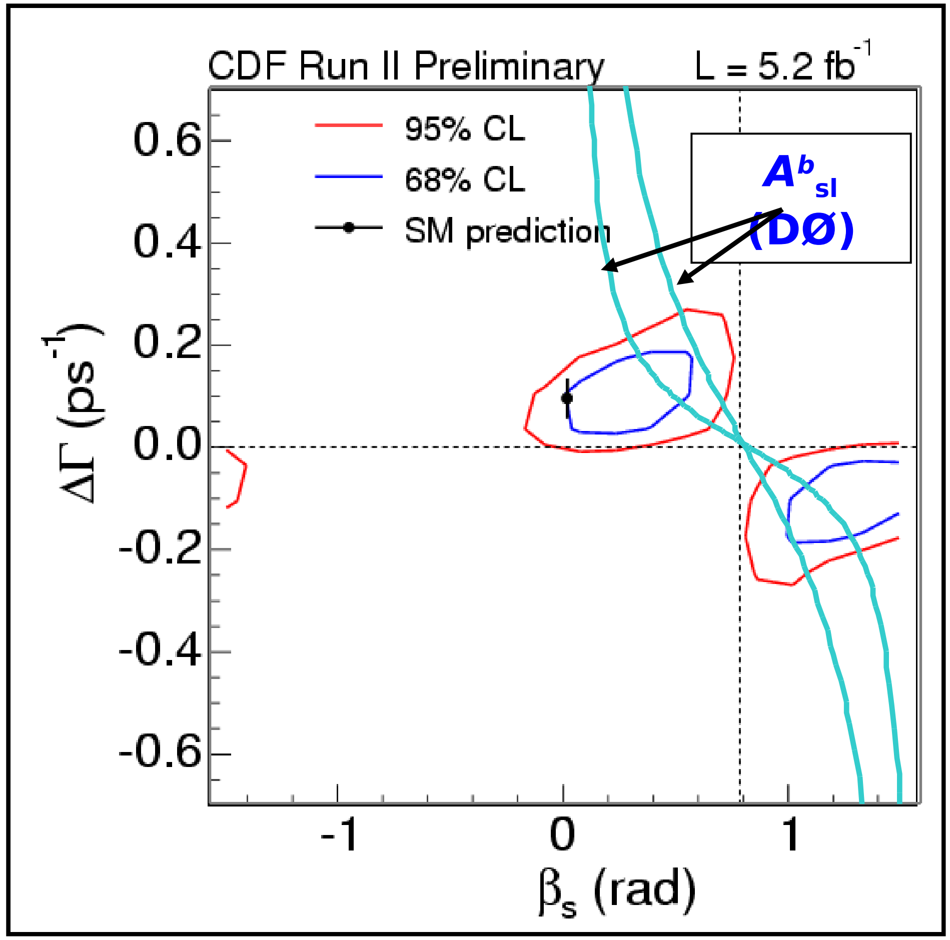
Consistency with other Results (III)



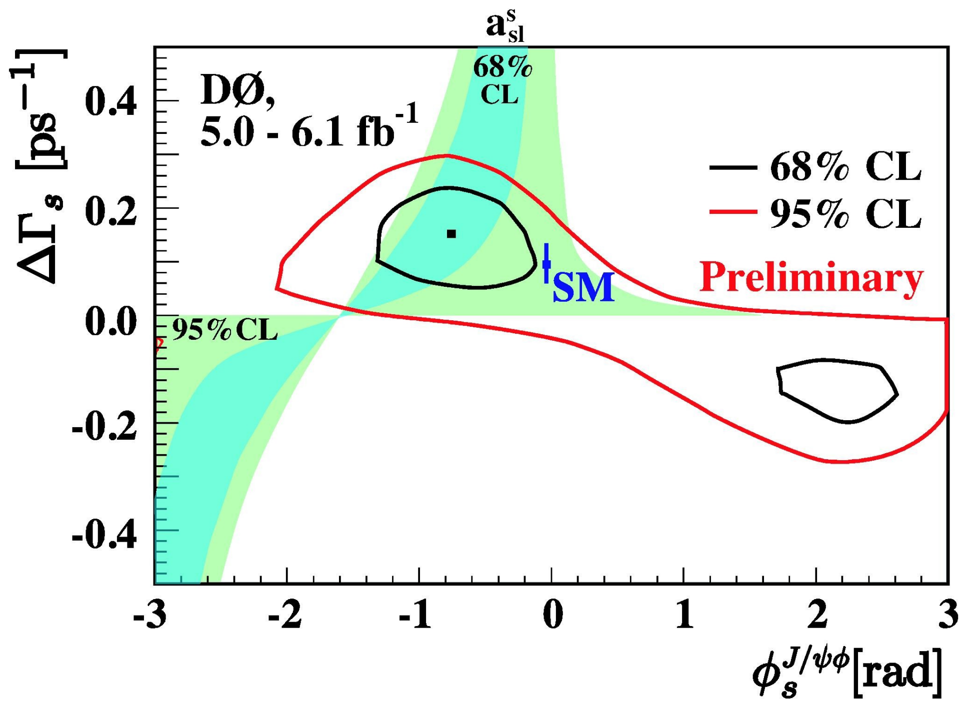
Consistent with measurement of
$\Delta\Gamma_s$ and Φ_s in $B_s \to J/\Psi\ \Phi$ decays at DØ ......

Consistency with other Results (IV)

.... and at CDF

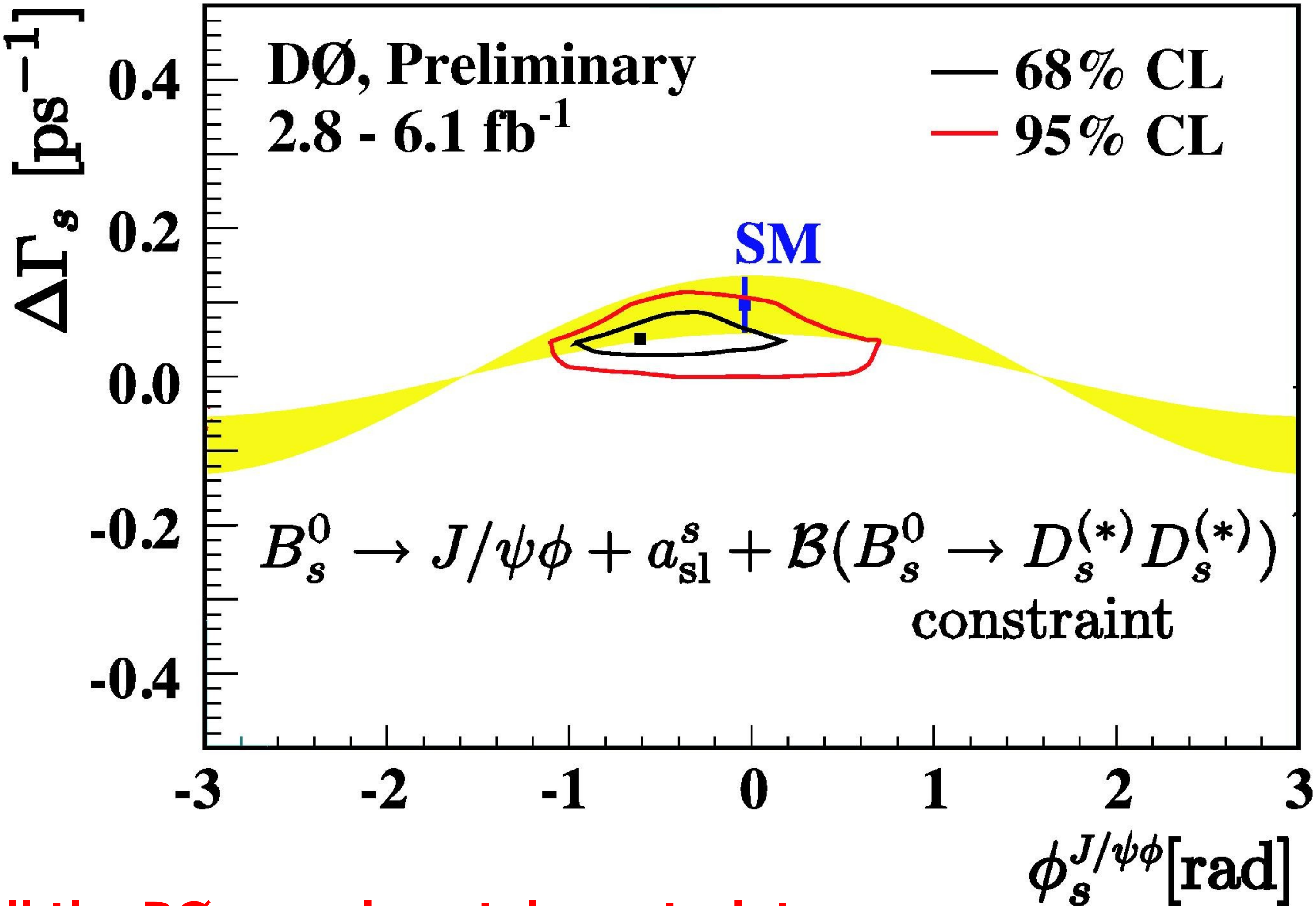


Consistency with Other Results (V)



Here the DØ combination of the two measurements of a^s_{sl} is compared to the measurement of $\Delta\Gamma_s$ and Φ_s in $B_s \rightarrow J/\Psi\ \Phi$ decays

DØ Combination



Using all the DØ experimental constraints

Conclusions (I)

We have made a new measurement of the like-sign dimuon asymmetry which is significantly different from zero

Under the assumption that is due to B physics we extract

$$\boxed{A_{\mathrm{sl}}^{b} = (-0.957 \pm 0.251\,(\mathrm{stat}) \pm 0.146\,(\mathrm{syst}))\%}$$

This result is consistent with all other measurements of CP violation in B mixing, but differs from the SM prediction by 3.2 standard deviations

Obtained using very little input from simulation, all tests show excellent consistency

Dominant uncertainty is statistical, precision can be improved

Conclusions (II)

Future prospects

DØ: additional data, further reduce dependence on MC and systematics

CDF: will try to repeat the measurement (but cannot flip magnetic field)

LHCb: pp collisions, can measure ratio of asymmetries a^s_{sl} and a^d_{sl} and obtain similar cancellation of systematics